AE 452 Aeronautical Engineering Design II
Air Loads

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Maneuver loads

\[ L\cos \phi \quad L\sin \phi \quad mV_{\infty}^2 / R \quad W \]

\[ \text{Top view} \]

\[ \text{Top view of horizontal plane} \]
Level turn

- The greatest air loads on an airplane usually come from the generation of lift during high-g maneuvers.
  \[ n = \frac{L}{W}, \text{ load factor and } n = \frac{1}{\cos\phi} \]

- The largest load the airplane is expected to encounter is called the limit load and the corresponding load factor is called the limit load factor.

- Ultimate load factor or the design load factor is the limit load multiplied by a factor of safety to account for material and workmanship quality, design errors, uncertainty, etc.

- Factor of safety = 1.5 \( \Rightarrow n_{\text{ultimate}} = 1.5 \times n_{\text{limit}} \).
## Typical limit load factors

<table>
<thead>
<tr>
<th>Category</th>
<th>$n_{\text{positive}}$</th>
<th>$n_{\text{negative}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>General aviation—normal</td>
<td>2.5 to 3.8</td>
<td>-1 to -1.5</td>
</tr>
<tr>
<td>General aviation—utility</td>
<td>4.4</td>
<td>-1.8</td>
</tr>
<tr>
<td>General aviation—aerobatic</td>
<td>6</td>
<td>-3</td>
</tr>
<tr>
<td>Homebuilt</td>
<td>5</td>
<td>-2</td>
</tr>
<tr>
<td>Transport</td>
<td>3 to 4</td>
<td>-1 to -2</td>
</tr>
<tr>
<td>Strategic bomber</td>
<td>3</td>
<td>-1</td>
</tr>
<tr>
<td>Tactical bomber</td>
<td>4</td>
<td>-2</td>
</tr>
<tr>
<td>Fighter</td>
<td>6.5 to 9</td>
<td>-3 to -6</td>
</tr>
</tbody>
</table>
Level turn

- **Stall limit** for the maximum load factor (**instantaneous turn**):

\[
L = n_{\text{max}} W, L = \frac{1}{2} \rho_{\infty} V_{\text{stall}}^2 C_{L,\text{max}} S
\]

\[
\Rightarrow n_{\text{max}} = \frac{\frac{1}{2} \rho_{\infty} V_{\text{stall}}^2 C_{L,\text{max}}}{W/S}
\]

- The speed at which the maximum lift is equal to the allowable structural load factor is the **corner speed** and provides the maximum turn rate for a given altitude.

- Modern fighters have a corner speed around 300-350 knots.
Level turn

• Corresponding turn rate:

\[ \psi = \frac{g\sqrt{n^2 - 1}}{V_\infty} \]

• Corresponding turn radius:

\[ R = \frac{V_\infty^2}{g\sqrt{n^2 - 1}} \]
V-n diagram

- V-n diagram depicts allowable load factors as a function of airspeed.
V-n diagram

• Corner velocity: the slowest speed at which the maximum load factor can be reached without stalling.

• Dive speed: represents the maximum dynamic pressure, $q_\infty$. The point representing maximum $q_\infty$ and $n_{limit}$ is important for structural design. Exceeding $V_{dive}$ may result in phenomena like wing divergence, control surface reversal, etc.

$$V_{dive} = 1.5 \times V_{cruise} \text{ or } V_{dive} = 1.2 \times V_{max} \text{ for subsonic airplanes}$$

$$M_{dive} = M_{max} + 0.2 \text{ for supersonic airplanes}$$
Sustained turn

• An aircraft will probably not be able to **maintain speed and altitude** while turning at the maximum instantaneous turn rate.

• **Sustained turn rate** is usually specified in terms of the maximum load factor at a given flight condition that the aircraft can sustain, e.g. 4-5g at M=0.9 at 30000 ft.

\[
T = D, \quad L = nW \Rightarrow n = \frac{T}{W} \frac{L}{D}
\]

• Load factor in a sustained turn increases when T/W and L/D increases.
Aerodynamic and structural limits on turn performance
Aerodynamic and thrust limits on turn performance
Pull-up maneuver

• At $t = 0$ ($\theta = 0$):

$F_r = L - W = W(n - 1) = m \frac{V_\infty^2}{R} = \frac{W}{g} \frac{V_\infty^2}{R}$

• Solving for turn radius:

$R = \frac{V_\infty^2}{g(n-1)}$

• Solving for turn rate:

$\dot{\psi} = \frac{V_\infty}{R} = \frac{g(n-1)}{V_\infty}$
Pull-down maneuver

• At $t = 0$ ($\theta = 0$):

\[ F_r = L + W = W(n + 1) = m \frac{V_\infty^2}{R} = \frac{W V_\infty^2}{g R} \]

• Solving for turn radius:

\[ R = \frac{V_\infty^2}{g(n+1)} \]

• Solving for turn rate:

\[ \dot{\psi} = \frac{V_\infty}{R} = \frac{g(n+1)}{V_\infty} \]
Gust loads

- The loads experienced when the airplane encounters a strong gust (when flying close to a thunderstorm or during clear air turbulence encounter) may exceed the maneuver loads.

![Gust encounter diagram](image)
Gust loads

- When an airplane encounters a **gust**, the effect is to **increase** the angle of attack:

  \[ \Delta \alpha = \tan^{-1} \left( \frac{U}{V_\infty} \right) \approx \frac{U}{V_\infty} \]

  \[ \Delta L = q_\infty S \left( C_{L\alpha} \Delta \alpha \right) = \frac{1}{2} \rho_\infty V_\infty S C_{L\alpha} U \]

  \[ \Delta n = \frac{\Delta L}{W} = \frac{\rho_\infty V_\infty C_{L\alpha} U}{2W/S} \Rightarrow \text{load factor due to a gust} \]

  \[ \Rightarrow \text{increases for aircraft with low wing loading!} \]
Gust loads

- The assumption that an airplane **instantly** encounters a gust and this gust instantly effects the airplane is **unrealistic**.
- Gusts follow **cosine-like intensity** increase allowing aircraft more time to react. This reduces the acceleration experienced by the airplane.
Gust loads

• **Gust velocity:**

\[ U = K U_{de}, \text{ } K: \text{gust alleviation factor} \]

\[ K = \frac{0.88\mu}{5.3+\mu}, \text{subsonic flight} \]

\[ K = \frac{\mu^{1.03}}{6.95+\mu^{1.03}}, \text{supersonic flight} \]

\[ \mu = \frac{2(W/S)}{\rho_{\infty}g\bar{c}\bar{C}_{L\alpha}}, \text{mass ratio} \]

\[ U_{de} = 30 \text{ ft/s, standard vertical gust, produces n=3g load factor, suitable for CS23 airplanes.} \]
Gust loads

Fig. 14.6 Derived equivalent gust velocities (transport).
Gust loads
Gust loads

Fig. 14.8 Combined V-n diagram.